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14. ABSTRACT

Project Themis is an in-house program within the Liquid Engines Branch of the Air Force Research Laboratory (AFRL). It focuses on investigation of liquid oxygen (LOX)/hydrocarbon high pressure combustion devices through subscale experimentation in combustion and inert conditions, theory development, and modeling and simulation (M&S). The Themis program has two goals: to minimize component risk and to mature new technologies that can be transitioned to future engine systems. The first helps AFRL technology demonstrators reduce risk by improving the fundamental understanding of these systems. The second focuses on the future by identifying new configurations, technologies, and materials for transition into future systems.

As part of a set of Themis experiments, a facility is being activated to test the effect of supercritical conditions on the mixing of fluids in a jet-in-crossflow (JICF) configuration. This research serves as risk reduction for AFRL programs. The experiment will simulate the geometry and high pressure conditions of a liquid rocket engine (LRE) component in a non-combustion environment using inert fluids. The experiment is designed to be modular and can accommodate various injection concepts. In the current experiment, radial jets of liquid nitrogen (LN2) will be introduced into a freestream flow mixture of argon and helium at supercritical pressure. These fluids will simulate dense LOX injected into a flow of low density combusted gases. The simulant fluids have been selected to achieve large density and momentum ratios. This configuration is designed to mature the understanding of the mixing process of variable density jets in a supercritical state.

This paper will describe the facility configuration, modeling of the facility using Sinda-Fluint and the challenges of activating a mothballed facility. It will also describe the experimental set-up, instrumentation and test matrix for the experiment. The data acquired from this experimental facility will enhance the understanding of mixing phenomena and provide validation data for M&S.

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Project Themis Supercritical Cold Flow Facility, Experiment Design and Modeling for the Study of Fluid Mixing

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Nomenclature

AF	=	Air Force
AFRL	=	Air Force Research Laboratory
C	=	circular
CO_2	=	carbon dioxide
CH_4	=	methane
CFD	=	computational fluid dynamics
Cv	=	flow Coefficient
DAQ	=	data acquisition system

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GN_2	=	gaseous nitrogen
He	=	helium
J	=	momentum flux ratio
JICF	=	jet in crossflow
LN_2	=	liquid nitrogen
LOX	=	liquid oxygen
LREs	=	liquid rocket engines
MR	=	mixture ratio
M&S	=	modeling and simulation
NIST	=	National Institute of Standards and Technology
PLC	=	programmable logic controller
S	=	slotted
TCA	=	thrust chamber assembly
ρ_{jet}/ρ_{gas}	=	jet-to-gas density ratio
$(\rho U^2)_{jet}/(\rho U^2)_{gas}$	=	jet-to-gas momentum flux ratio

I. Introduction

One of Project Themis' major efforts is a cold flow mixing study to determine the effects of large density ratios on fluidic mixing at high pressure. Experimental data on jet mixing of dissimilar fluids under supercritical conditions has not been well characterized in the literature. Air Force research programs are designing liquid rocket engines (LREs) that operate in these poorly understood regimes. Current design work on these LREs rely more than ever before on the accuracy of modeling and simulation (M&S) programs. It is therefore critical to have experimental data covering the relevant regimes in order to validate these computer models. The Themis cold flow mixing study will provide this necessary experimental data. The experiment will acquire data in an inert, cold-flow environment that will simulate the extreme thermodynamic conditions of a LRE while eliminating issues of data acquisition and instrumentation survivability present under typical combustion conditions.

II. Background and motivation

A. Initial motivation for experiment

Current LRE component design work relies significantly on computational M&S. This paradigm is counter to the once common "design-build-test-fail" practice. The potential advantage of using M&S is the ability to fabricate hardware that is able to meet design requirements without the expense and delays of test driven modifications. M&S, however, demands validation to mitigate risk. Current M&S tools are not adequately validated in the extreme environment of high performance LRE components due to a lack of heritage data for high pressure devices and a limited knowledge base for scaling laws applicable in the relevant operating conditions.

Liquid rocket systems operate with fluids that have extreme disparities in both temperature and density. Mixing is a critical aspect of the design so fluid species are mixed such that threshold levels of flow uniformity are attained. These threshold levels are critical for issues of engine performance and material survivability. Furthermore, quick mixing is often desirable in these systems to provide engine weight savings by minimizing the size of heavy high pressure components. This study will examine a design specific approach where fluids are mixed entirely through fluidic means without the use of intrusive mixing devices.

B. Configuration description

The Themis cold flow study is initially investigating a radial fluid mixing geometry. For this experiment, a mixing device is devised that has two specific zones, shown on Figure 1: Zone 1 consists of low density axial freestream flow while Zone 2 is the injection/mixing zone where high density secondary fluid is introduced radially.

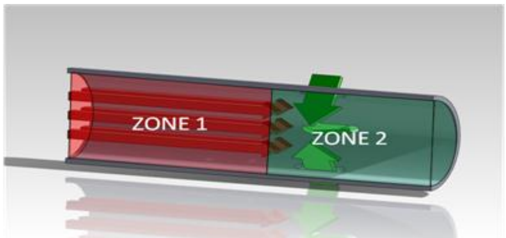

Figure 1. Mixing Device Zones

Computational fluid dynamics (CFD) analyses of this design predict that this mechanism of secondary injection can result in efficient mixing. The physics behind the actual mixing behavior, however, are not entirely understood.

This radial injection configuration can be reduced to an extension of the basic jet in crossflow (JICF) scenario where the jet is represented by the secondary radially injected fluid and the free stream is the crossflow fluid as shown in Figure 2.

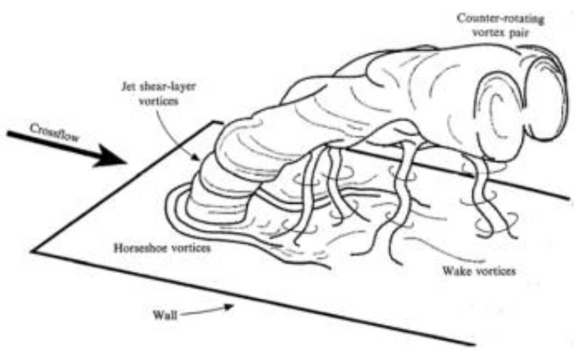

Figure 2. Classic Jet in Crossflow Representative of Radial Injection [1]

C. Validation

Validation of M&S is vital to meet the various goals of the AF engine programs. High performance LRE systems operate at extreme temperatures and pressures which are exceedingly difficult to reproduce for experimental validation. Furthermore, extracting the required data from these hostile environments is often not possible

The Themis cold flow experiment is an attempt to create a compromise between the realistic environment of the combustion device and a lab bench study. The cold flow environment allows acquisition of data not currently attainable in a hot fire environment. Intrusive measurements in the flow field of combustion devices are limited by instrumentation survivability. Lab scale studies, where data is much more accessible, cannot provide the combination of pressure and Reynolds number on a scale large enough to allow for flow field mapping.

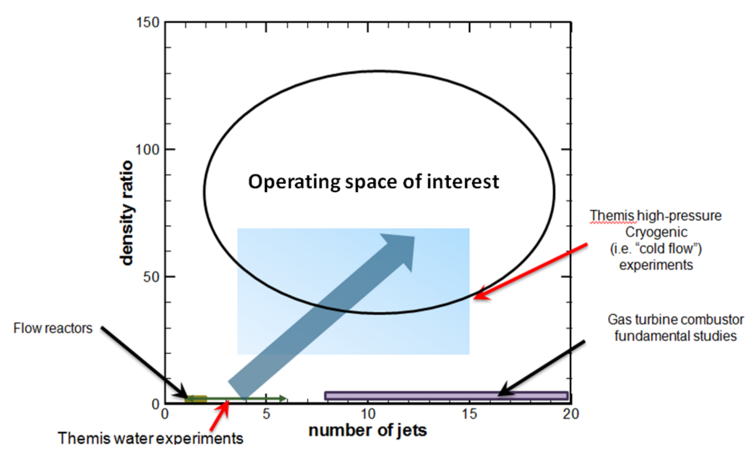

Figure 3. Jet Number and Density Ratio Map

The supercritical conditions and large density ratios to be investigated in this study represent a significant departure from most studies of jet mixing. Up to now there hasn't been a strong need to investigate the effects of these conditions on fluidic mixing. Studies motivated toward the understanding of gas turbine engines do not explore the regimes of supercritical pressure and large jet-to-freestream density ratios. The little work that has been done in these areas point to the fact that key mixing related phenomena, such as jet spreading rate, are quite different at supercritical conditions [2]. Representative pressure and density are keys to obtaining results that can anchor the modeling tools. The Themis cold flow test will simulate the supercritical nature and variable density of a hot fire application in an accessible and inert environment. Figure 3 shows the operating space of interest for the Themis cold flow experiments. Themis cold flow experiments will expand the current experimental data base of variable density ratio jets.

III. Cold Flow System Configuration Definition

A. Cold flow experiment and constraints

The constraints on the cold flow program were numerous. Factors considered in the cold flow experiment and facility configuration included: 1) maximizing operating pressure; 2) operating at supercritical conditions; 3) capability of wide range of density ratios (ρ_{jet}/ρ_{gas}) and momentum ratios $(\rho U^2)_{jet}/(\rho U^2)_{gas}$; 4) adoption of preferably safe, non-toxic fluids; 5) concept of operations that yield easily repeatable and reproducible flow conditions at low cost; 6) consideration of availability and cost of fluids; 7) cold flow hardware that allows rapid configuration change and accommodates mixing diagnostics.

Consideration of Factor 1 resulted in ~1000 psia as an approximate limit on maximum test pressure. Table 2 gives the critical properties (Factor 2) of some of the initial fluid candidates, along with the densities at 1000 psia and ambient temperature.

Table 1. Properties of Several Initial Cold Flow Fluid Candidates

Fluid	Temperature (°R)	Pressure (psia)	Phase	Density (lb/ft^3)	Critical P (psia)	Critical T (°R)
N_2	535	1000	supercritical	4.89	493	227
He	535	1000	supercritical	0.68	33	9
H_2O	535	1000	liquid	62.45	3206	1165
O_2	535	1000	supercritical	5.79	737	279
RP-1	535	1000	liquid	50.35	332	1223
CO_2	535	1000	liquid	47.06	1071	548
CH_4	535	1000	supercritical	3.15	673	343
R113	535	1000	liquid	98.84	492	877
R12	535	1000	liquid	84.17	600	693

The density ratio range (Factor 3) is a function of fluid selection. Momentum ratios can be achieved by appropriate velocity selection (jet and gas), given the density ratio of the fluids selected as simulants. Sample density ratios for a variety of options from the candidate fluid list were generated. For this survey, gaseous nitrogen, both below and above ambient, were included. The resultant density ratios are presented in Table 2. Water was excluded from initial examination because of the difficulty in achieving supercritical conditions of the water and freestream gas mixture.

Table 2. Density Ratios for Sample Combinations of Initial Cold Flow Fluid Candidates

Simulant Fluids Jet/Freestream	Press (psia)	Phase Jet/Freestream	Jet Temp (°R)	Free-stream Temp (°R)	Jet Density (lb/ft^3)	Free-stream Density (lb/ft^3)	Density Ratio Jet/Freestream
CO_2/N_2	1000	liquid/supercritical	535	535	47.1	4.89	9.6

CO_2/N_2	1000	liquid/supercritical	400	1480	73.2	1.72	42.6
CO_2/CH_4	1000	liquid/supercritical	535	535	47.1	3.15	15.0
CO_2/CH_4	1000	liquid/supercritical	400	830	73.2	1.81	40.4
RP-1/N_2	1000	liquid/supercritical	535	535	50.4	4.89	10.3
RP-1/N_2	1000	liquid/supercritical	535	2030	47.1	1.26	37.4
R12/N_2	1000	liquid/supercritical	535	535	84.2	4.89	17.2
R12/N_2	1000	liquid/supercritical	535	1210	84.2	2.10	40.2
CO_2/He	1000	liquid/supercritical	535	535	47.1	0.68	69.7
N_2/He	1000	supercritical/supercritical	248	535	27.1	0.68	40.1

Table 2 includes some options with heating or cooling (or both) of the fluids in each combination (e.g., CO_2/N_2, CO_2/CH_4, RP-1/N_2, and R12/N_2). By fluid heating and cooling, it is possible to achieve a wider range of density ratios for a given fluid combination. Program constraint Factor 4 (safe non-toxic fluids) and Factor 5 (low cost simple operations) make options with fuels (e.g., RP-1, CH_4) unattractive since simple fluid venting into the atmosphere could be precluded. Similarly, options with high temperature heating would require substantial investment in heating and insulation equipment. Ambient mixtures of R12 and N_2 would not result in conditions above the critical temperature of R12 (thus, violating Factor 3). Simple, non-heated combinations can achieve a wide density ratio range (CO_2/N_2 ~10, CO_2/He ~70, and N_2/He ~ 40). But no single combination delivers a wide range by itself. In addition, it was determined that use of "benign" fluids would greatly facilitate operational and safety constraints.

B. Cold flow fluid options addressing facility, operational, and experimental constraints

It was determined that using nitrogen as the diluent species and helium as the freestream species could achieve a wide range of density ratios. Both nitrogen and helium satisfy the safety, toxicity, and availability concerns. The conditions necessary to obtain a wide range of density ratios are given in Table 3.

Note from Table 3, ambient helium gas is used (operationally desirable), but chilled nitrogen gas is needed to achieve the necessary density ratio range. Several issues were identified with the cold nitrogen gas requirements: filling a vessel with cold nitrogen gas at prescribed and repeatable conditions complicates operations; variation of the nitrogen properties during expulsion presents flow control and experimental difficulties; for the high density ratio case, the nitrogen is close to the critical point possibly resulting in two phase flow during expulsion. One solution is the use of liquid nitrogen versus cold gas. Storage, flow control, and phase control of liquid nitrogen (LN_2) is operationally relatively straightforward. However, the only density ratio that can be achieved is ~74 which is well above the range of interest.

Table 3. Density Ratio Capabilities of N_2/He Gas Mixtures.

	Low Density Ratio Cold Flow P=1000 psia	**High Density Ratio** Cold Flow P=1000 psia
Freestream Species	**Helium**	**Helium**
Temperature (°R)	535	535
Tcrit (°R)	9	9
Pcrit (psia)	33	33
State	Supercritical	Supercritical
Density (lb/ft^3)	0.676	0.676
Jet Species	**Nitrogen**	**Nitrogen**
Temperature (°R)	303	239
Tcrit (°R)	227	227
Pcrit (psia)	493	493
State	Supercritical	Supercritical
Density (lb/ft^3)	11.77	30.89
Initial Density Ratio,(ρ_{jet}/ρ_{gas})	**17.4**	**45.7**

A second approach was formulated: mix the helium with a second high molecular weight gas yielding freestream gas density variations which could tolerate liquid nitrogen as the diluent. Two safe and inert candidate gases were identified: neon and argon. The minimum and maximum density ratio of each mixture is given in Table 4.

Table 4. Density Ratio Ranges for Helium/Neon and Helium/Argon Mixtures.

	Helium/Neon Mixture Cold Flow P=1000 psia	**Helium/Argon Mixture** Cold Flow P=1000 psia
Freestream Species	**Helium/Neon**	**Helium/Argon**
Temperature (°R)	535	535
Helium/Second Gas Tcrit (°R)	9/80	9/271
Helium/Second Gas Pcrit (psia)	33/395	33705
State	Supercritical	Supercritical
Pure Helium/Second Gas Density (lb/ft^3)	0.676/3.40	0.676/7.22
Jet Species	**Liquid Nitrogen**	**Liquid Nitrogen**
Temperature (°R)	150	150
Tcrit (°R)	227	227
Pcrit (psia)	493	493
State	Supercritical	Supercritical
Density (lb/ft^3)	49.80	49.80
Initial Density Ratio,(ρ_{jet}/ρ_{gas})		
Minimum (pure Second Gas)	14.6	6.9
Maximum (pure Helium)	**73.7**	**73.7**

Each of the gas mixtures can meet the range needed to span the density ratios of interest. However, the helium/argon mixture can reach a minimum density ratio a factor of ~2 lower than neon. The advantages of neon are its low critical temperature and pressure (~80°R and 395 psia respectively). However, neon is very expensive and was precluded based on cost and availability (Factor 6). On the other hand, argon (being the third most abundant gas in the atmosphere) is readily available in bulk and is relatively inexpensive. The disadvantage of argon is its higher critical temperature (44°R higher than nitrogen) which necessitates closer attention to the final mixed gas conditions which will be discussed below. Based on these considerations, the helium/argon mixture was selected for the freestream gas simulant with liquid nitrogen as the jet simulant.

C. Initial experiment configuration and facility interface requirements

The initial cold flow system configuration is shown schematically in Figure 4. The liquid nitrogen mass flow was controlled with a cavitating venturi. The helium and argon mass flows were controlled by sonic venturis. The test chamber pressure was controlled by sonic outlet orifice which could be either fixed or variable (e.g., valve).

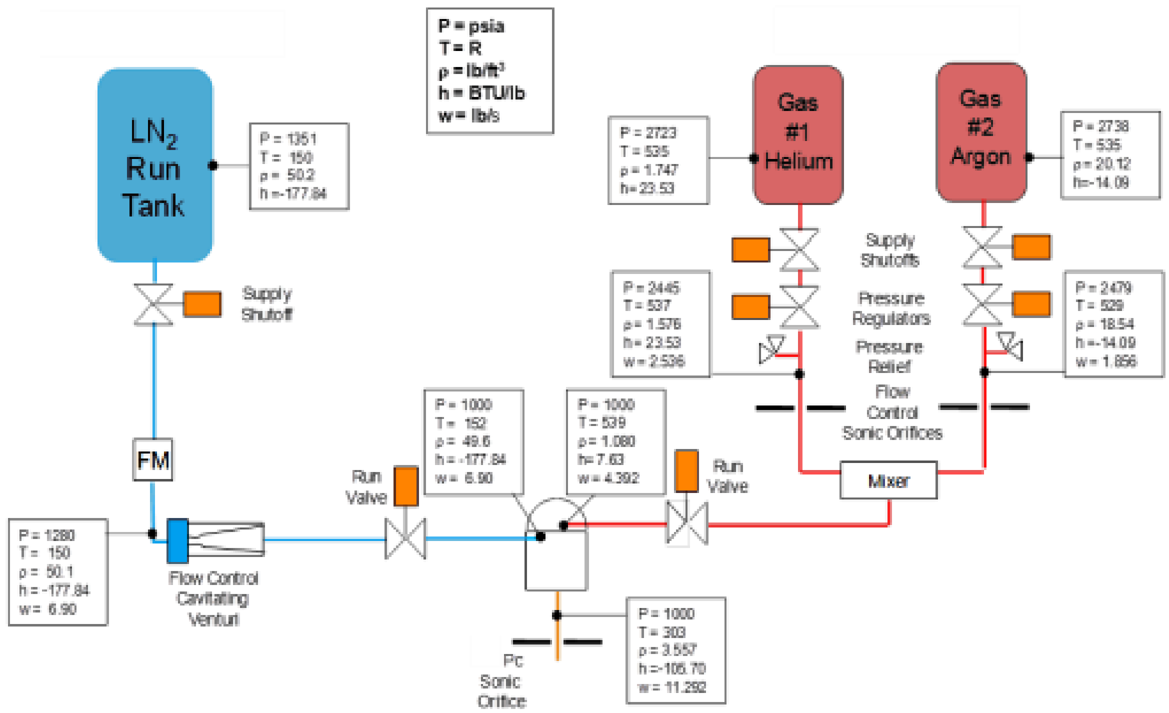

Figure 4. Initial Cold Flow Configuration Schematic.

The pressure schedule shown in Figure 4 was derived based on initial estimates of component characteristics. The state point properties are based on National Institute of Standards and Technology (NIST) calculations. The "tank" pressures shown in Figure 4 are the minimum facility interface pressures that must be supplied to satisfy the pressure drop requirements from the interface to the experiment. The facility interface conditions were computed with a model that characterized each fluid flow circuit. Each circuit was complete with all the relevant flow components (lines, filters, regulators, flow control devices, valves, experimental hardware, etc.). The model could be used to compute both nominal and off-design conditions. It should be noted that the system shown in Figure 4 was derived when the size of the long facility lines was unknown (as were many of the facility component Cv's). Placeholder values were used which later proved to be much larger than actual. Reliable documentation was unavailable and line sizes were later measured by ultrasonic means.

The absolute flow rates were selected to provide a balance between hardware fabrication, room for diagnostics, and wall effect mitigation. The freestream gas flow was chosen to provide a relevant mass flow rate of interest. The enthalpy of the cold freestream gas is insufficient to keep the overall outlet mixture above the critical temperature of argon or nitrogen if high amounts of the LN_2 is injected. Thus, the LN_2 flow rate was reduced so that the final mixture temperature was above the critical temperature of the argon. The summary of the preliminary cold flow conditions shown in the Figure 4 schematic are given in Table 5. As part of the cold flow experimental effort, the tests will be run over a wide range of jet-to-gas momentum ratios by varying the jet injection velocity while keeping mass flows and test article pressure constant. In addition, a wide range of density ratios (~7-74) may be tested by varying the helium/argon mixture ratio.

Table 5. **Summary of Preliminary Cold Flow Conditions**

Helium/Argon Preliminary Cold Flow Conditions Freestream Species	Property Value Helium/Argon
Temperature (°R)	535
Helium/Argon Tcrit (°R)	9.4/271
Helium/Argon Pcrit (psia)	33/706
State	Supercritical
Total Flowrate (lb/sec)	4.39
Helium/Argon Flowrate, (lb/sec)	2.53/1.86
Density (lb/ft^3)	1.09
Jet Species	**Liquid Nitrogen**
Temperature (°R)	150
Tcrit (°R)	227
Pcrit (psia)	493
State	Liquid at Supercritical Pressure
Total Flowrate (lb/sec)	6.9
Density (lb/ft^3)	49.8
Mixed Gas	**He/Ar/N_2**
State	Gas
Temperature (°R)	300
Density (lb/ft^3)	3.6
Key Ratios	
Initial Density Ratio (ρ_{jet}/ρ_{gas})	45.7
Final Density Ratio (ρ_{jet}/ρ_{gas})	13.8
Initial Momentum Ratio $(\rho U^2)_{jet}/(\rho U^2)_{gas}$	Variable: 5-50

D. Facility configuration definition

It was determined that an existing AFRL facility was well suited for the Themis cold flow experiment. A test cell was selected that contained an insulated cryogenic oxygen tank that could be used for the LN_2 supply. Adjacent to the test cell is a cryogenic storage bunker that contained a helium supply tank with existing high pressure lines and flow control elements capable of delivering high pressure helium to the test cell. An additional existing gas supply tank was located in a fuel bunker adjacent to the test cell. Some existing lines and flow control elements were routed between this fuel bunker and the test cell. Accordingly, the tank in the fuel bunker was assigned to the argon supply circuit. The previously described flow circuit models were enhanced to include the flow component elements from the experiment to the LN_2 tank in the test cell, to the helium tank and to the argon tank. Cold flow experiment test time is limited by the fluid capacity in the storage tanks. For the LN_2 circuit, the entire tank volume can be used. The helium and argon run times are limited by the blow down from initial pressure down to its minimum circuit interface requirement. Once the gas storage tank pressures fall below that needed to supply the experiment, additional run time can be recovered only by refilling the gas storage tanks. The “residual” gas in the tanks is unavailable for testing. The enhanced flow circuit model showed a surprising result: the argon pressure drop from the inlet of the sonic venturi to the fuel bunker tank was very low (less than 25 psi) while the helium pressure drop from the cryogenic storage bunker was almost 2000 psi. Thus, the helium pressure drop set severe limitations on test time and on utilization of the expensive helium. Careful study showed that the helium system was designed to deliver relatively small flows of the lower density helium to the test cell as evidenced by the low Cv components and small line diameter. The nominal 2.5 lb/s helium flow resulted in a large pressure drop. On the other hand, the fuel cell system, being designed for hydrogen, had high Cv components and large line sizes which resulted in low pressure drops for the high density argon gas. The test time limitation and the high unusable helium residual were untenable. A shift in paradigm was proposed: use the original helium tank for the high density argon flow; use the hydrogen tank in the fuel bunker for the low density helium flow. This architecture reconfiguration solved the pressure drop and helium utilization problem. The pressure drops from the sonic venturi inlets to the tank outlets was only ~200 psi for both argon and helium. This architecture reconfiguration was adopted and is now the current experimental baseline.

Assuming the revised configuration and that the gas storage tanks start at high pressure, the argon tank can supply a test duration similar to the LN_2 tank run time capability before recharge is necessary. The helium tank can supply about half of the LN_2 tank run time capability before recharge. Allotting ~15 seconds for a mixing experiment run, the present tankage configuration can provide many individual runs before any of the fluids require resupply.

IV. Test Hardware Design

A. Test Article

The test article is designed as a simplified representation of many possible LRE components. The assembly allows for the controlled introduction of the high pressure simulant fluids. They key requirements for the design include: (1) pressure rating of 1500 psi, (2) modularity for changing diluent jet configuration, (3) uniform delivery of mass flow rate to jets, and (4) the ability to measure the mixedness of the fluids at axial locations downstream of the jet injection plane.

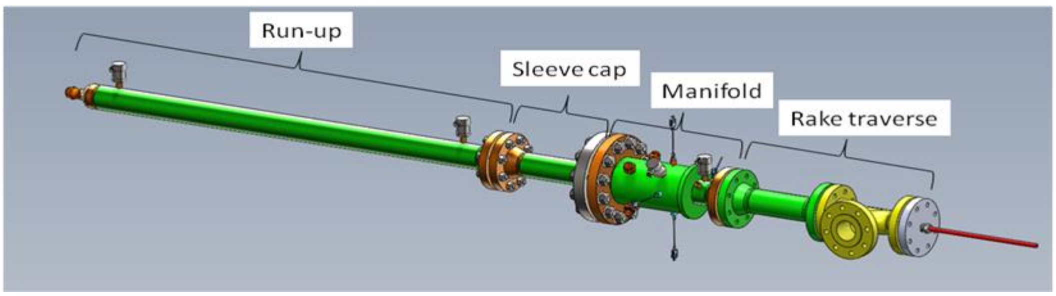

Figure 5. The Four Section Test Article Assembly

The test article is divided into four primary sections: run-up, sleeve cap, manifold and rake traverse as shown on Figure 5. All sections are fabricated using 304 stainless steel, schedule 80 piping and class 600 flanges. The length of the device is 14.5 feet. The run-up section acts as the transition between the facility mixed gas flow and the test section. The argon/helium mixed gas flow is transported to the mixing section through the run-up and sleeve cap. The manifold section acts as the transition between the facility LN_2 flow and the mixing section. The internals of the manifold and flow path of simulant fluids are diagrammed in Figure 6. LN_2 enters the manifold at four radial locations and flows along the outside of the sleeve to the jet ports.

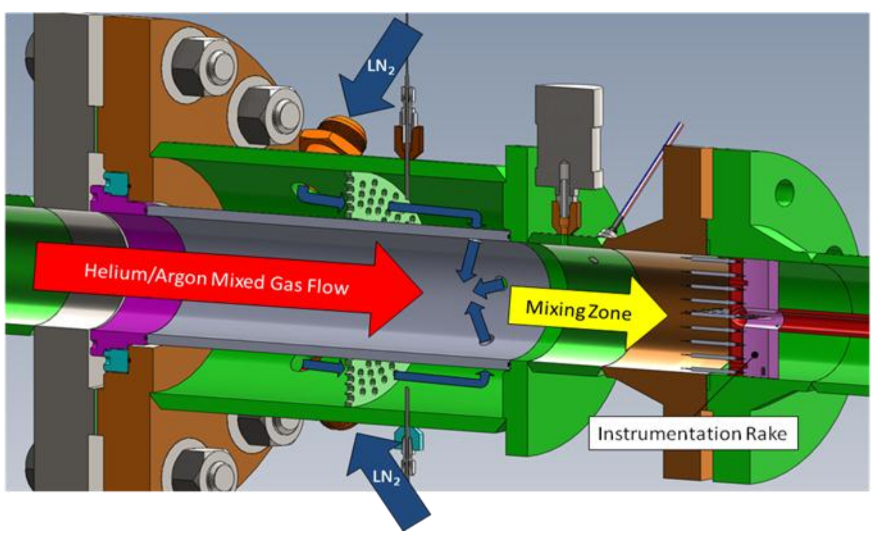

Figure 6. Simulant Fluid Flow Path in the Test Article Manifold Section

A key aspect of the test article design is the ability to change the jet configuration. This is accomplished through the use of a modular sleeve insert. The sleeve section has a series of radial ports machined into one end. These serve as orifices through which the oxidizer simulant is introduced into the freestream flow of helium and argon. Sleeve sections can be swapped out to vary the jet configuration. The removable sleeve is sealed in place through an assortment of retaining rings, o-rings and gaskets. The sealing mechanism used to secure the modular sleeve is shown in Figure 7.

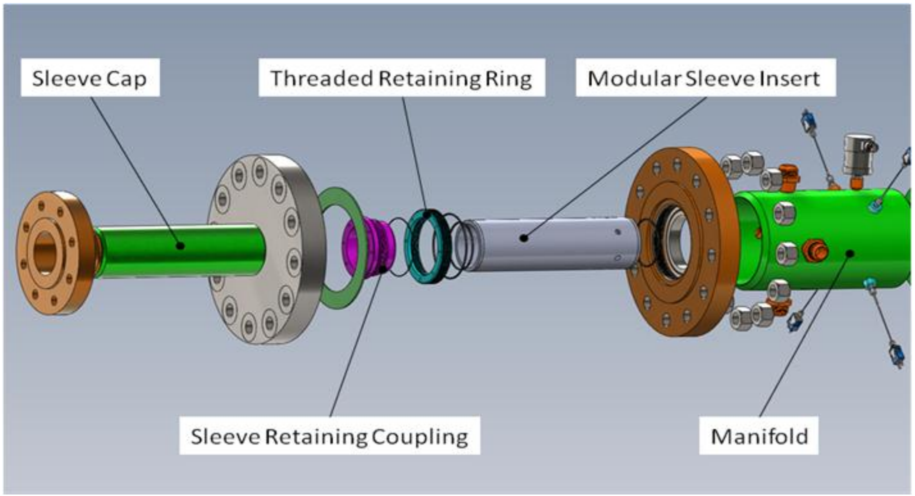

Figure 7. Exploded View of Test Article

The final section of the test article is the rake traverse. The rake traverse is comprised of two piping sections: a straight section and a tee. Residing inside this section is a movable instrumentation rake. The rake is designed to travel axially through the piping section. The rake head is supported on a stinger that can be rotated or moved axially to change the probe spatial location of the rake instrumentation as seen in Figure 8. The hollow stinger houses the hot-wire probe cabling. The rake stinger passes through a Swagelok sealed port on a tapped blind flange on the far thru-run of the tee section as shown in Figure 5. The tee flow thru-branch will be fitted with a back pressure orifice to set the test chamber pressure.

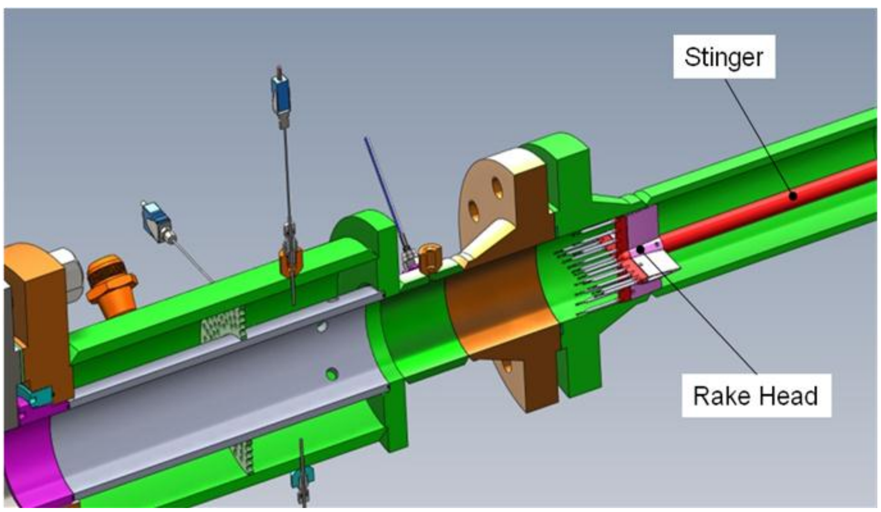

Figure 8. Test Article Instrumentation Rake

B. Instrumentation

The test article and facility are instrumented with an array of sensing devices to monitor both facility operation and provide data for analysis. The test article is fitted with an array of pressure transducers, thermocouples, and an instrumentation rake of hot-wire anemometer sensors. The layout of the externally mounted sensors is shown in Figure 9. It is worth noting that PT 8-103 is a high frequency, wall mounted pressure transducer that will be used to capture pressure perturbations in the area immediately downstream of the jet mixing zone. A Kulite CT-375 series will sample at 20 kHz at this location.

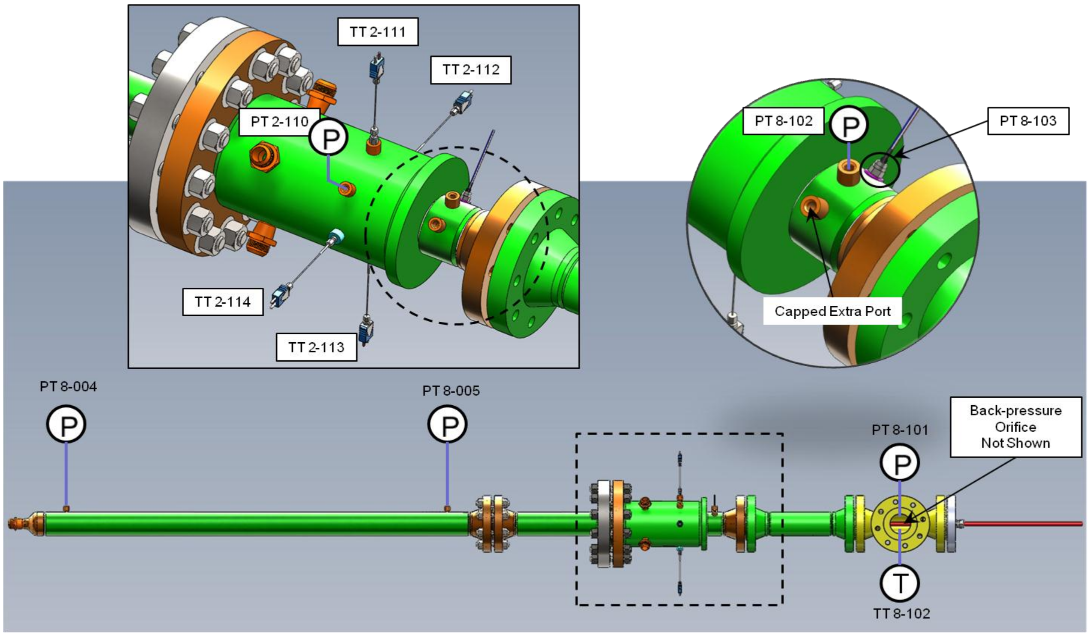

Figure 9. Test Article External Instrumentation Locations.

The instrumentation rake is comprised of an array of 19 hot-wire anemometer probes that will operate in a "cold wire" mode. The low thermal mass of these sensors allows for extremely fast temperature frequency response. Figure 10 shows the two hot-wire probes models made by TSI, Inc that are baselined for the rake: 1201-20 and 1210-T1.5. The design of the rake included an in depth analysis of sensor sensitivity, accuracy, repeatability, frequency response and robustness. The sensitivity of the individual probes is approximately 0.9 degree Fahrenheit. The sensors were tested by heating with a pulsed laser in air. The measured time constants were in line with math models used to project to the actual working fluids. Response rates of 1.3 ms are conservatively predicted in a LN_2 medium. The sensors were tested at conditions twice the expected dynamic pressure of the experiment and survived without calibration shift. The robustness testing is shown in Figure 11. The anemometer probes will be used to capture the mean flow field temperatures.

Figure 10. Hot-wire Anemometry Probes Baselined for Instrumentation Rake

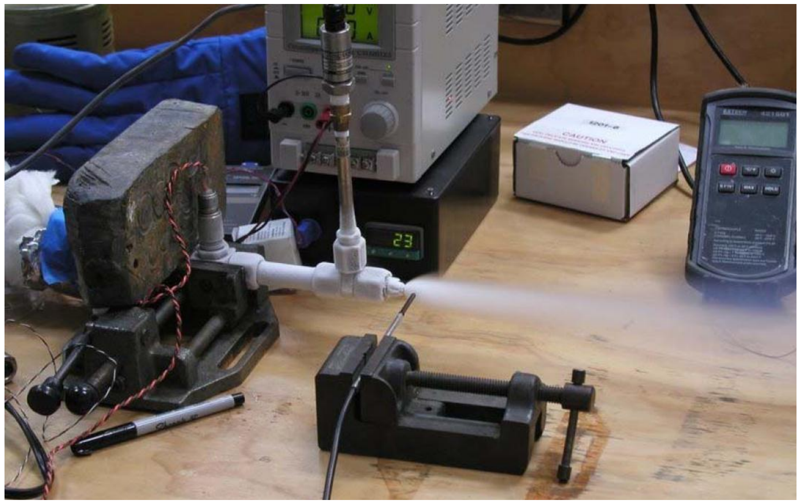

Figure 11. Robustness Testing of Sensor at High LN_2 Dynamic Pressure

C. Test Matrix

The test matrix is shown in Table 6 with the targeted operating parameters. These parameters address the data needed in the regimes identified in Figure 3. To understand the test matrix, naming conventions are defined. First, multiple test configurations are planned for the test article sleeves. The test matrix will be separated into Test Series, Subtests, and Runs to provide organization and documentation numbering for each test. The breakdown for each is defined as follows:

- A test series is set up for the geometric shape of the injection holes. The first test series will be done for circular geometry holes and the second test series will be done for rectangular slotted holes. A test series is separated into several subtests.
- Each subtest involves changing the test article sleeve design using the same geometric shape but each design may vary the number and/or size of holes to vary the momentum flux ratio (J). The first test series is a circular geometry. The first subtest in this test series will target a momentum flux ratio of 10, the second subtest will target 20, the third subtest will target 30, and the fourth subtest will target 40. Each subtest will consist of two test runs.
- Test runs are performed within each subtest target the same operating conditions. The purpose is to verify the repeatability of the test data. The first subtest in the first test series uses a sleeve design with circular holes and a target momentum flux ratio of 10. Two test runs are planned at this condition.

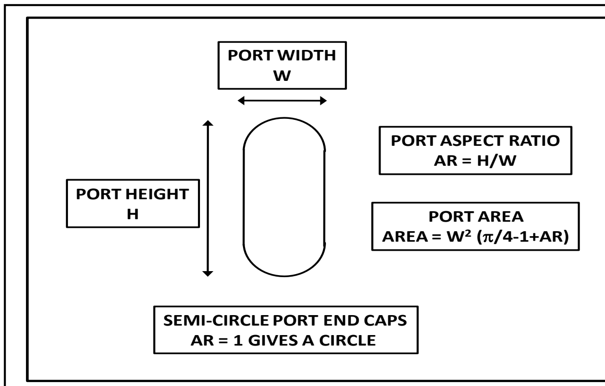

Figure 12. Aspect Ratio Definition for Jet Ports on Modular Sleeve

The nomenclature (identifier) for each test will be given by the following:

{Port Geometry} - {# of Ports} – {Aspect Ratio} – {Momentum Flux} – {Run Number}

Port geometry for the identifier would either be circular (C) or slotted (S). Number of Ports would be 4, 6, or 8. Aspect Ratio is 1 for a circle and varies for the slots. The aspect ratio of the ports is diagrammed in Figure 12. Momentum flux is 10, 20, 30, or 40. Run number is either 1 or 2 but could continue on as high as necessary.

Table 8. Test matrix for cold flow test experiment.

Test ID	Subtest	Run	# of Injection Ports	Momentum Flux Ratio (J)	Aspect Ratio	Diameter (in)	Argon/Helium		LN_2 I/F Pressure	
							Pressure (psia)	Temp (°R)	Pressure (psia)	Temp (°R)
C-4-1-10-1	1	1	4	10	1	0.519	1000	530	1000	150
C-4-1-10-2	1	2	4	10	1	0.519	1000	530	1000	150
C-4-1-20-1	2	1	4	20	1	0.436	1000	530	1000	150
C-4-1-20-2	2	2	4	20	1	0.436	1000	530	1000	150
C-4-1-30-1	3	1	4	30	1	0.394	1000	530	1000	150
C-4-1-30-2	3	2	4	30	1	0.394	1000	530	1000	150
C-4-1-40-1	4	1	4	40	1	0.367	1000	530	1000	150
C-4-1-40-2	4	2	4	40	1	0.367	1000	530	1000	150
C-6-1-10-1	5	1	6	10	1	0.423	1000	530	1000	150
C-6-1-10-2	5	2	6	10	1	0.423	1000	530	1000	150
C-6-1-20-1	6	1	6	20	1	0.356	1000	530	1000	150
C-6-1-20-2	6	2	6	20	1	0.356	1000	530	1000	150
C-6-1-30-1	7	1	6	30	1	0.322	1000	530	1000	150
C-6-1-30-2	7	2	6	30	1	0.322	1000	530	1000	150
C-6-1-40-1	8	1	6	40	1	0.299	1000	530	1000	150
C-6-1-40-2	8	2	6	40	1	0.299	1000	530	1000	150
C-8-1-10-1	9	1	8	10	1	0.367	1000	530	1000	150
C-8-1-10-2	9	2	8	10	1	0.367	1000	530	1000	150
C-8-1-20-1	10	1	8	20	1	0.308	1000	530	1000	150
C-8-1-20-2	10	2	8	20	1	0.308	1000	530	1000	150
C-8-1-30-1	11	1	8	30	1	0.279	1000	530	1000	150
C-8-1-30-2	11	2	8	30	1	0.279	1000	530	1000	150
C-8-1-40-1	12	1	8	40	1	0.259	1000	530	1000	150
C-8-1-40-2	12	2	8	40	1	0.259	1000	530	1000	150
S-4-3.6-10-1	1	1	4	10	3.59	0.899	1000	530	1000	150
S-4-3.6-10-2	1	2	4	10	3.59	0.899	1000	530	1000	150
S-4-2.6-20-1	2	1	4	20	2.60	0.651	1000	530	1000	150
S-4-2.6-20-2	2	2	4	20	2.60	0.651	1000	530	1000	150
S-4-2.2-30-1	3	1	4	30	2.17	0.542	1000	530	1000	150
S-4-2.2-30-2	3	2	4	30	2.17	0.542	1000	530	1000	150
S-4-1.9-40-1	4	1	4	40	1.90	0.476	1000	530	1000	150
S-4-1.9-40-2	4	2	4	40	1.90	0.476	1000	530	1000	150
S-6-2.5-10-1	1	1	6	10	2.47	0.617	1000	530	1000	150
S-6-2.5-10-2	1	2	6	10	2.47	0.617	1000	530	1000	150
S-6-1.8-20-1	2	1	6	20	1.81	0.452	1000	530	1000	150
S-6-1.8-20-2	2	2	6	20	1.81	0.452	1000	530	1000	150
S-6-1.5-30-1	3	1	6	30	1.52	0.379	1000	530	1000	150
S-6-1.5-30-2	3	2	6	30	1.52	0.379	1000	530	1000	150
S-6-1.3-40-1	4	1	6	40	1.34	0.335	1000	530	1000	150
S-6-1.3-40-2	4	2	6	40	1.34	0.335	1000	530	1000	150
S-8-1.9-10-1	1	1	8	10	1.90	0.476	1000	530	1000	150
S-8-1.9-10-2	1	2	8	10	1.90	0.476	1000	530	1000	150
S-8-1.4-20-1	2	1	8	20	1.41	0.352	1000	530	1000	150
S-8-1.4-20-2	2	2	8	20	1.41	0.352	1000	530	1000	150
S-8-1.2-30-1	3	1	8	30	1.19	0.298	1000	530	1000	150
S-8-1.2-30-2	3	2	8	30	1.19	0.298	1000	530	1000	150
S-8-1.1-40-1	4	1	8	40	1.06	0.265	1000	530	1000	150
S-8-1.1-40-2	4	2	8	40	1.06	0.265	1000	530	1000	150

The technical success criteria for passing from one subtest to the next are as follows:

- Critical instrumentation data has been obtained from each of the test runs that can be used in the validation of analytical modeling associated with mixing of the two fluid streams.
- Each subtest was conducted safely per requirements.
- The two test runs in each subtest are repeatable. Each Subtest second run is designed to match the same operating conditions as the first run. .

V. Facility Overview

A. Facility selection

An AFRL Test Area was chosen as the location for the cold flow experiment. The existing facility infrastructure met many of the criteria that were needed to conduct the experiment including: 1) high pressure/high volume tankage, 2) high pressure/large diameter piping, 3) existing flow control valves and pressure regulators, 4) remote control room facility operation through programmable logic controller (PLC), 5) continuous supply of high pressure gaseous nitrogen and 6) high speed, multi-channel data acquisition system. The test area is shown in Figure 13. The selected test cell was near an existing cryogenic run tank that is suitable for LN_2. The cell had sufficient space for the test article. Argon and helium run tanks reside in cryogenic storage bunker and fuel bunker, respectively.

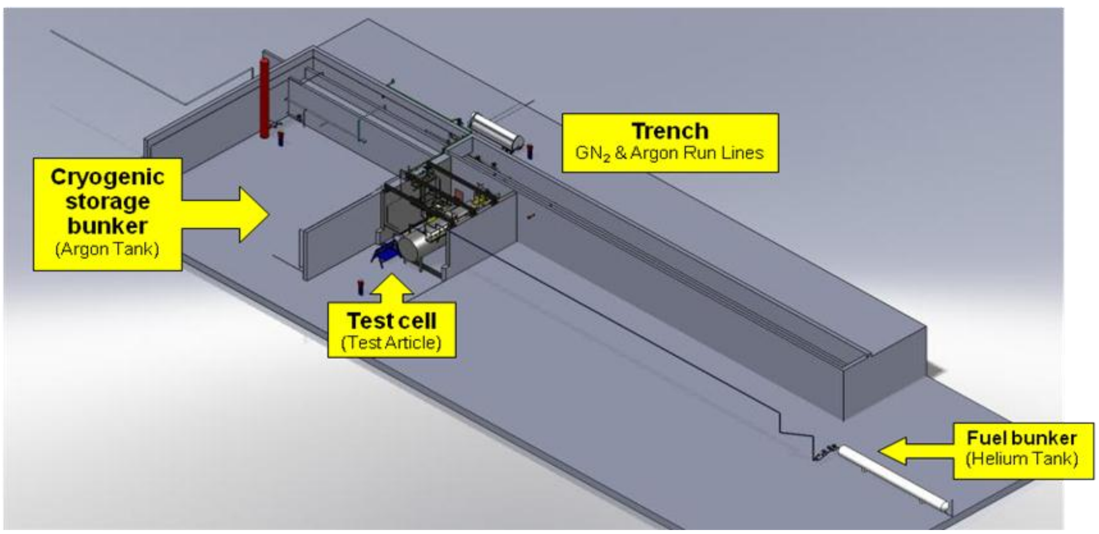

Figure 13. Test Facility

Figures 14, 15, 16 and 17 provide schematic representations of the four primary fluid control elements of the facility: 1) GN_2 pressurization system, 2) LN_2 flow system, 3) argon flow system, 4) helium flow system. These diagrams are simplifications of the actual fluid networks and do not show many of the critical flow components that exist in the system including hand isolation valves, pressure relief valves, check valves and filters. The GN_2 circuit shown in Figure 14 depicts how the LN_2 run tank is pressurized from the facility nitrogen supply cascade. This system is used to pressurize the LN_2 tank during preliminary low flow chill down operations and during testing. The LN_2, argon and helium circuits of Figures 15, 16 and 17 diagrams the flow from the three primary system run tanks to the test article. The LN_2 circuit is fully contained in test cell. LN_2 flow rate is controlled through the use of a cavitating venturi .A turbine flow meter is also on the run line. The argon and helium systems employ a calibrated sonic venturi to control fluid mass flow rate. Inlet pressures to the sonic venturis are set using a remotely controlled dome regulator. It is worth noting that the argon and helium circuits combine in a mixer prior to flowing into the test article. The mixer that joins the two gas flow circuits is a simple tee connection and line length adequate for mixing.

In the schematics, red lines represent electrical connections for control systems that are wired to the Allen Bradley PLC. These wiring circuits are used to energize solenoids for pneumatic valve actuation, monitor limit-switch valve position signals, and provide remote control setting capability of pressure regulators. All test cell pressure transducers are vented for zero-calibration by the activation of a single solenoid valve. Green lines in the schematics represent electrical data transmission wiring to the data acquisition system (DAQ). Blue lines represent the flow paths of GN_2, LN_2, argon and helium. Items located in the test cell are delineated by a grey dashed line rectangle.

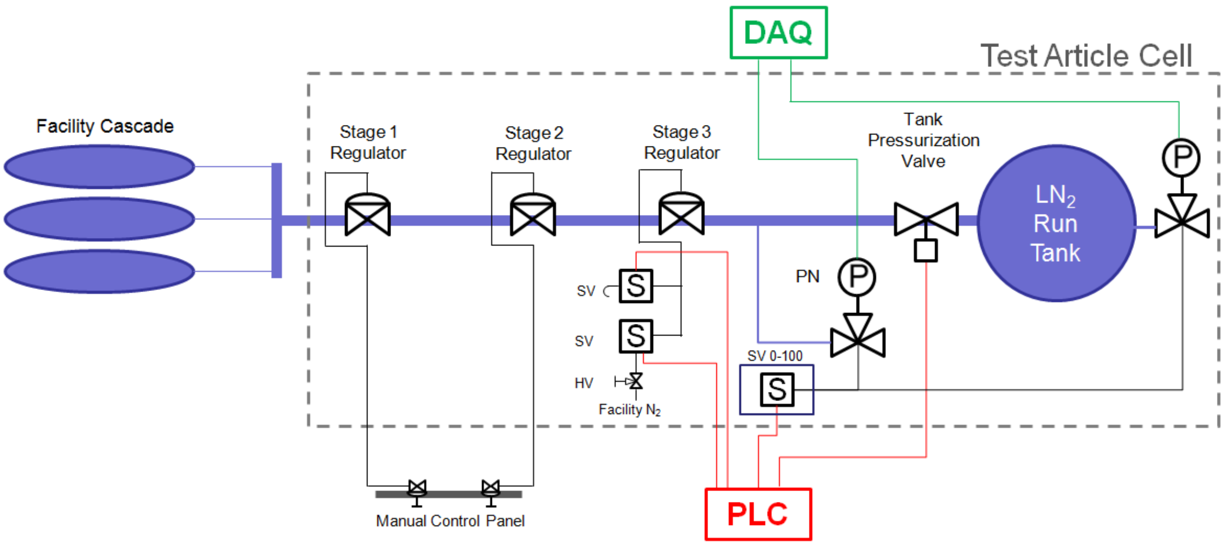

Figure 14. Gaseous Nitrogen Pressurization System

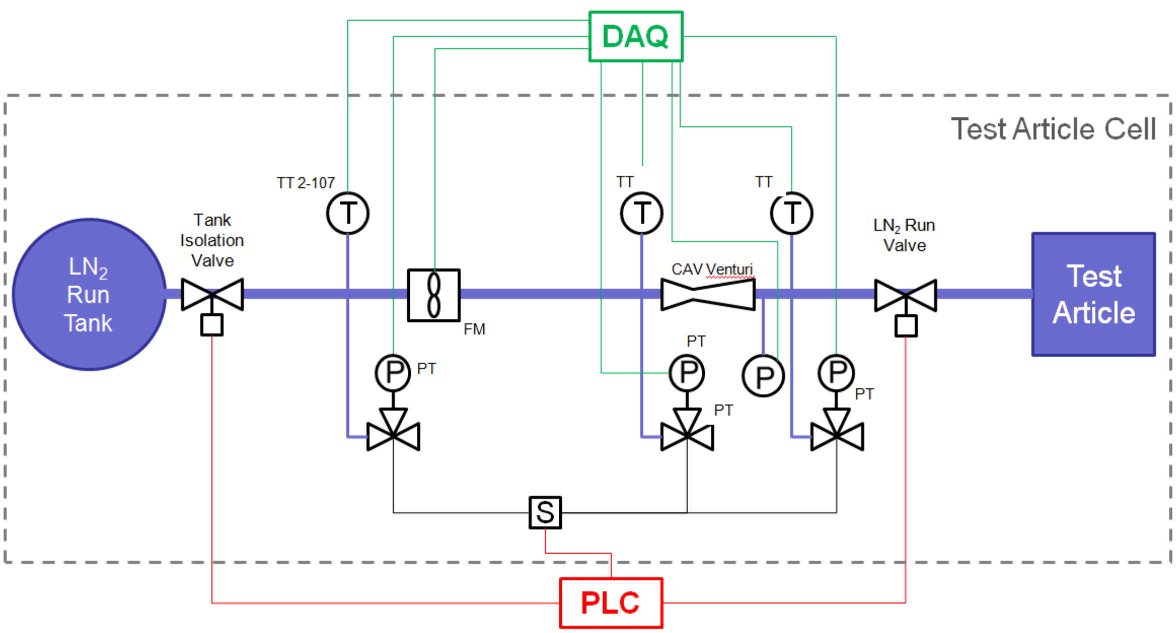

Figure 15. LN_2 Circuit

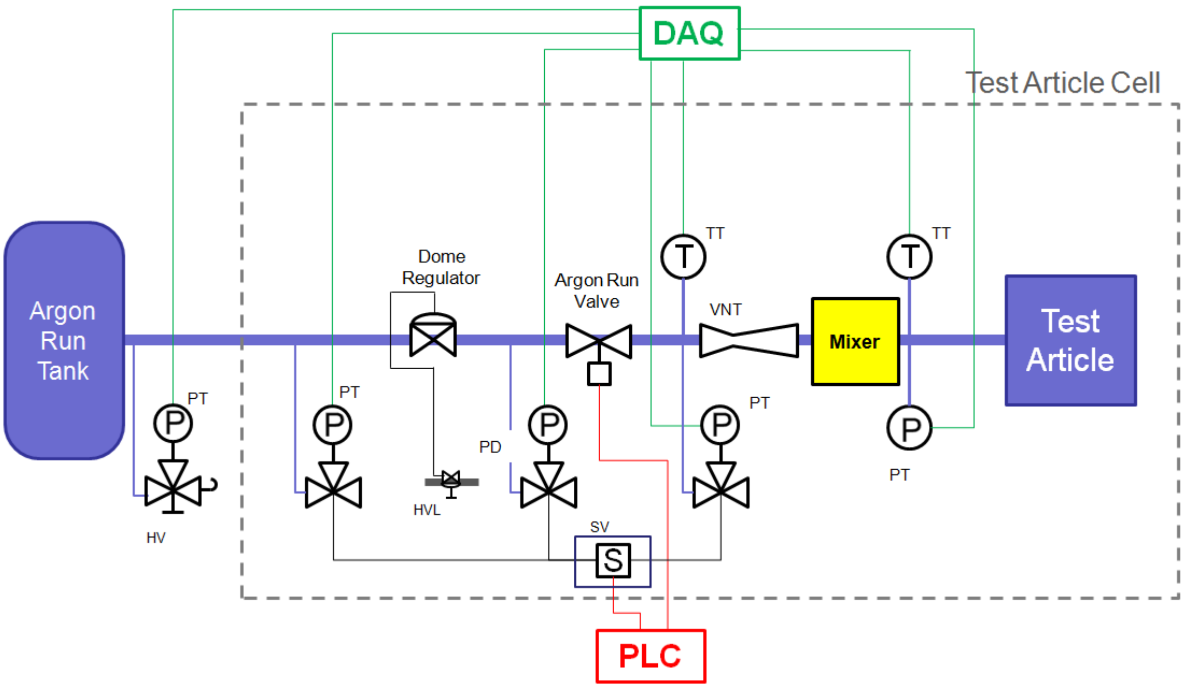

Figure 16. Argon Circuit

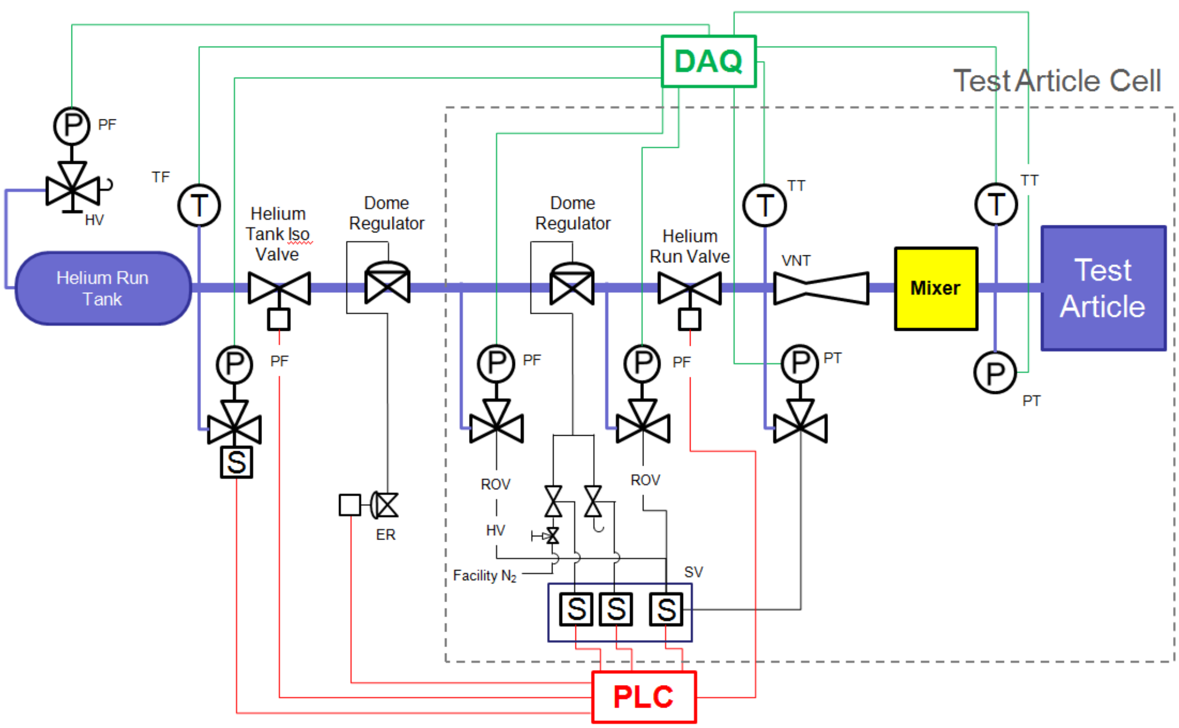

Figure 17. Helium Circuit.

B. Support Hardware

The LN_2 tank in the test cell was originally used as a LOX supply vessel. The LOX was supplied from standard trailers which were trucked to the facility site. The requisite fill lines and controls are already in place. The tank will be filled with LN_2 using the same procedures and fill systems as was the LOX. A fluid supply logistic diagram is shown in Figure 18. Liquid nitrogen will be delivered and stored in a low pressure vacuum jacketed storage tank located in the cryogenic storage bunker. It will be used to replenish the LN_2 run tank as the test series dictates. All components in the existing LOX system are rated to handle the colder LN_2.

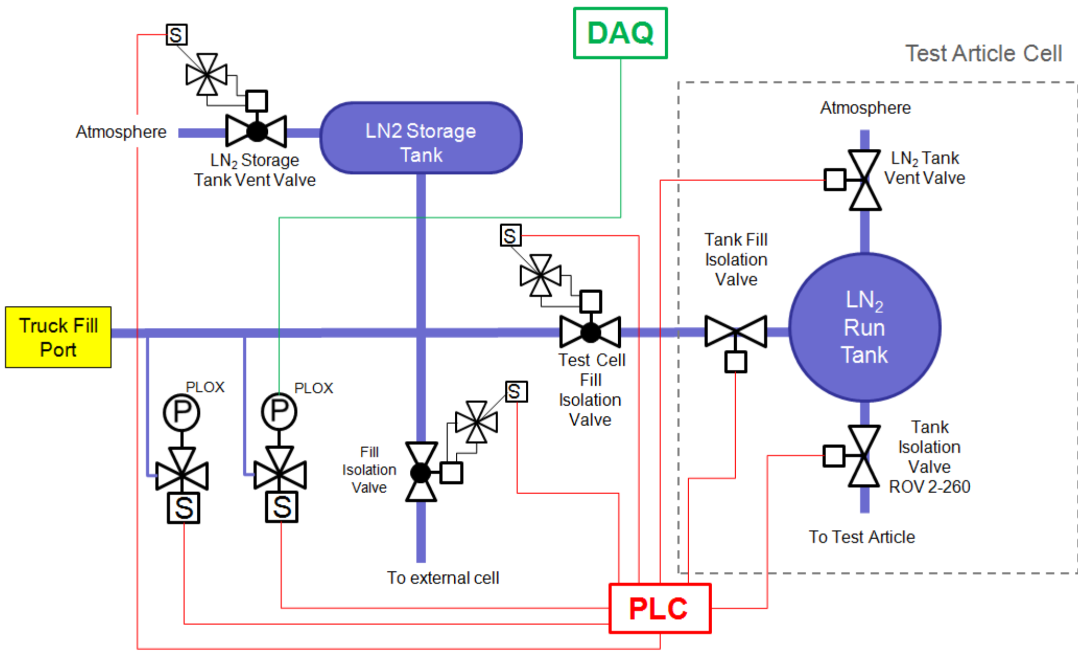

Figure 18. Control System and Logic for LN2 Delivery and Facility Storage.

The helium and argon tanks will be supplied by standard tube trailers initially pressurized to ~2400 psi that will be trucked into the facility. The argon tank will take one argon tube trailer to pressurize it to the desired maximum. The helium tank will take four helium tube trailers to pressurize it. After the tube trailer and gas supply tank pressures are equalized, the remaining gas in the tube trailer is pumped from the trailer into the supply tanks using the gas booster system described below. The argon transfer will take ~12 hours of pumping time. The helium transfer will require ~96 hours of pumping time for the four trailers.

To transfer gas from tube supply trailers into the high pressure argon and helium supply tanks, a gas booster system was needed. Since helium is expensive, minimizing the residuals left in the tube trailer was important. Preliminary calculations indicated that the gas transfer times could be long (~days). Thus, pumping systems that could operate at low final trailer pressures (e.g., ~100 psi), could pump to high supply tank pressures, could keep pumping times reasonable, and could operate reliably and automatically were essential.

The gas booster system uses low pressure (typically under 200 psi) facility GN_2 to power the pumps. The pumps have special "dry air" seal packages to ensure long life when using facility GN_2 to power the pumps. Because pumping times are very

Figure 19. Gas Booster System for Gas Transfer

long, the gas booster system is designed to operate in an unattended mode with automatic shutoff provisions when desired conditions are attained. Figure 19 shows the gas booster system built for the gas transfer tasks. As seen in Figure 19, the system is mounted on a mobile pallet that is easily transported.

VI. System Modeling Activities

C. Design and off-design baseline analysis

From the onset of the Themis program, a fluid supply system model was formulated which considered all of the experiment fluids and flow circuits (i.e., LN_2, helium and argon) from the experiment hardware outlet and going upstream to the fluid storage tanks. The model accounted for all of the line, fitting, and fluid component (valves, regulators, filters, venturis, etc.) pressure drops and established a pressure drop schedule that could be used to establish facility interface requirements. Both nominal and off-design fluid flows are easily accommodated. Similarly, adding or modifying components to increase fidelity is straightforward and is continually being implemented as the system maturity improves. The model was used to examine the many “what ifs” to quantitatively sort out various configuration concepts. For example, the model was used to identify the problem in the original helium storage and delivery concept. It subsequently was used to establish the significant system benefit from “switching” the argon and helium in their respective flow circuits. The baseline system incorporated flow control venturis for each fluid. Those venturis have been calibrated. The system with the actual venturi performance characteristics is given in Figure 20. Required tank interface pressures have gone up slightly due to somewhat lower venturi Cd values. However, the changes are quite small and should not impact nominal operation. Since the fidelity of the flow components from the experiment to the facility storage tanks is much improved, the minimum tank interface pressures shown in Figure 20 are representative of the actual minimum tank pressures that can be tolerated while still satisfying the required pressure budget.

The state point data was derived from NIST real fluid sources. NIST real fluid mixture predictions were used for the hot gas simulant mixed gases and for the mixture of all the fluids in the mixing experimental hardware. While the exit mixed gas temperature is quite low (~300°R) it is still above the critical temperatures of both argon and nitrogen. As previously stated, the LN_2 flow rate was specifically chosen to assure this condition. Any freestream condensation of the argon was considered as a complication to the understanding of the mixing processes. In addition, condensation could adversely affect the primary mixing diagnostic which is a spatially and temporally sensitive temperature measurement.

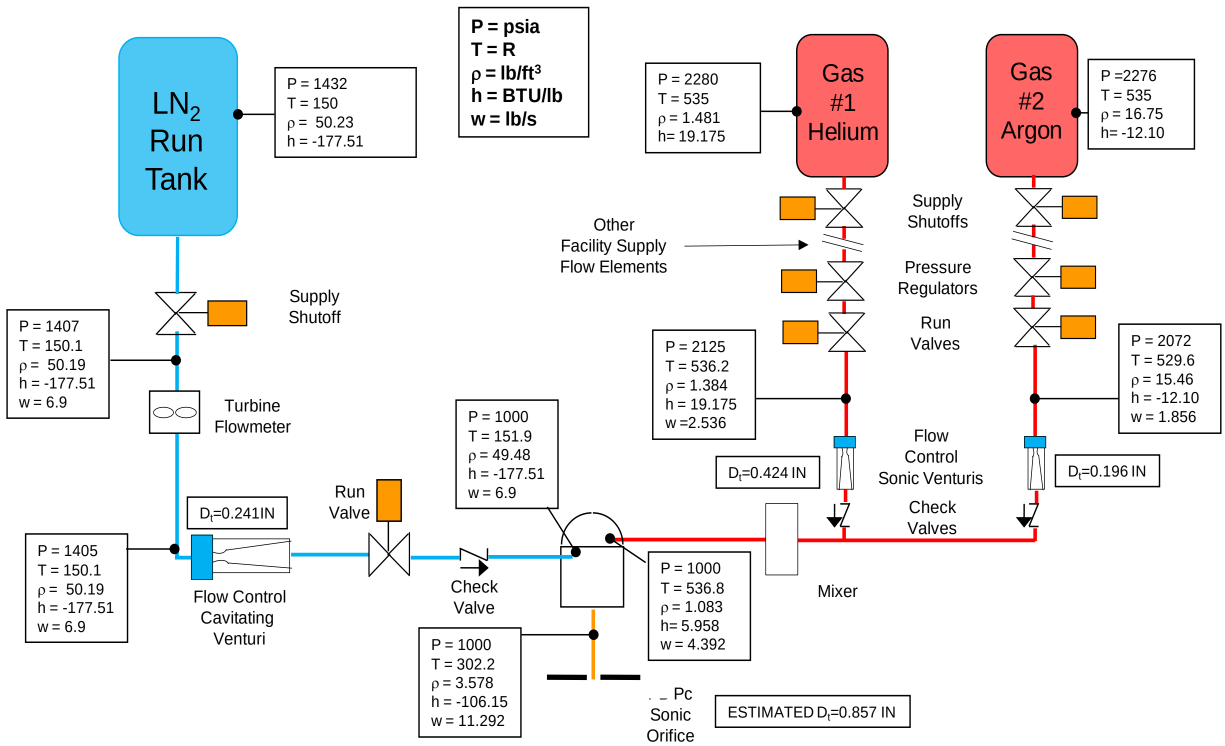

Figure 20. Current Experiment Configuration with Calibrated Flow Control Venturis

The test cell has also been modeled using the Sinda/Fluint analysis tool. Several aspects of the facility have been modeled including the argon fluid circuit, the helium fluid circuit, the LN_2 fluid circuit, and pressurization modeling including fluid and thermal heat transfer in the ullage for pressurizing the LN_2 run tank with GN_2.

Sinda/Fluint is a commercial product developed and marketed by Cullimore and Ring Technologies, Inc. It is a state-of-the-art, one-dimensional, network-solver-type analysis code. Sinda/Fluint models are created in a graphic user interface called Sinaps. This is a circuit style sketch pad interface for constructing a flow network. A portion of a sample network diagram is shown in Figure 21 for the helium system. The diagram is labeled such that it can be correlated to the Test Area piping and instrumentation diagram (PID). The Sinaps diagram for this circuit begins with the helium storage tank (not shown), and ends at the argon/helium mixer. Points in between include piping, filters, regulators, and valves. The fluid model includes both lumps and paths where the lumps are fluid elements that contain volume (such as pipes or tanks) and are represented with the "Helium.52" inside of them (which is the fluid model designation). The lumps are connected via paths and this path is where the pressure drop mechanisms are employed. A path can represent the friction loss in a section of pipe, a valve pressure loss, a filter pressure loss, a regulator reduction in pressure or any other type of flow device.

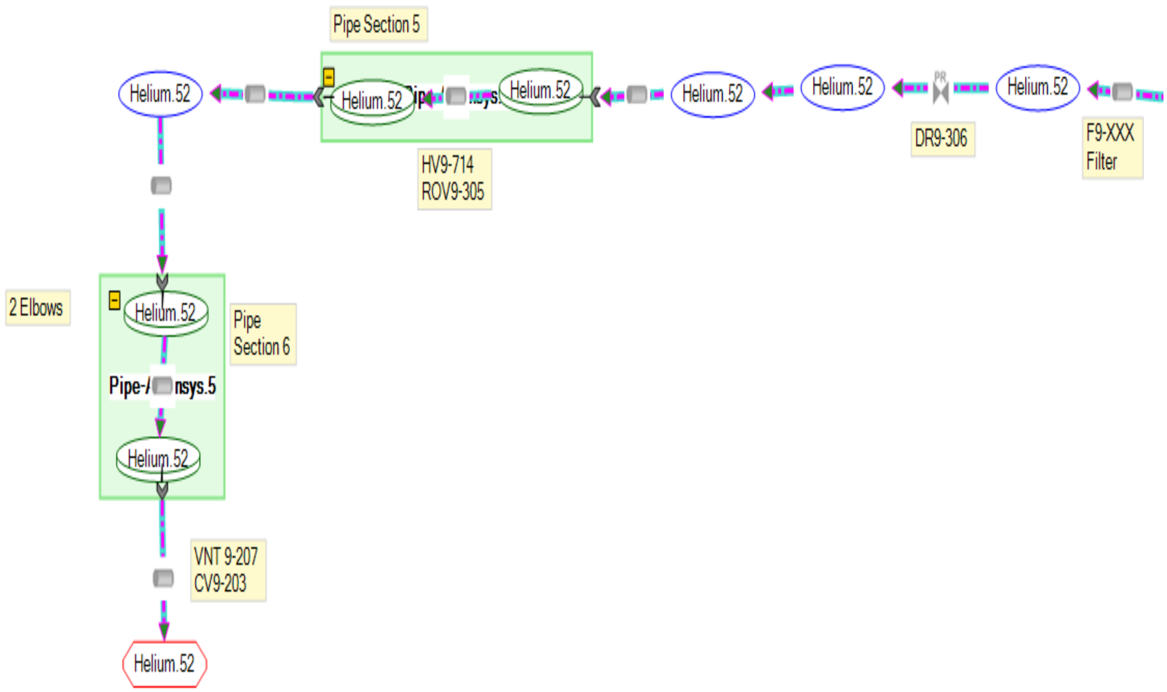

Figure 21. SINDA/FLUINT Helium Fluid Network Sample Diagram

The existing facility model consists of three separate fluid sub-models for the LN_2, helium and argon systems that have been discussed previously in the paper. The models include paths from the storage tank to the mixer. The objectives of the model are as follows:

- Simulate the steady state operating conditions of the mixing experiment
- Estimate the valve Cv's where existing valve loss coefficients are not known
- Perform transient modeling if anomalies are noted during facility shakedown tests
- Determine if pressurization of GN_2 over LN_2 in the run tank will be an issue

One of the current issues with all the facility fluid modeling is the lack of component specifications for the existing components in the system. Many of these components were installed long ago and specifications and acceptance test records are not currently available. Therefore, when looking at the pressure drops through the system, most of the components had no Cv data which is critical to determining pressure drop. The Sinda/Fluint model was performed using representative Cv data for similar components but this issue will certainly affect the modeling results. This is probably one of the largest areas of uncertainty in the cold flow experiment pressure budgets.

In order to address Cv uncertainty, a series of shakedown tests will be performed on the facility prior to conducting the experiments. These shakedown tests will be used to determine pressure drops through each of the fluid systems. There is a limited amount of instrumentation in each of the helium, LN_2, and argon systems. Thus, determining the pressure drop of each component will not be possible. In order to achieve the target flow rates, it will be critical to set the targeted inlet pressures for the flow control venturis. The shakedown tests should allow the gathering of sufficient data for better characterization of the fluid system performance. The pressure regulator settings upstream of the venturis will likely require some refinement as a result of these shakedown tests. From the shakedown tests, the Sinda/Fluint model will be used to help re-estimate specific regulator target values necessary for venturi inlet pressure requirements. It is expected that recalibration after each test should minimize the shakedown test effort.

Another key aspect of the Sinda/Fluint model is the ability to model transients, including the opening transient of a valve and pressure oscillations such as water hammer. Although transient issues for the mixing experiment are not anticipated, the shakedown tests are expected to verify this assumption.

One of the more complex modeling tasks was the GN_2 pressurization ullage model for the LN_2 run tank. This was an important consideration in determining how much GN_2 is required to maintain target pressure in the LN_2 run tank. In the Sinda/Fluint model, a single Fluint lump represents the liquid nitrogen in the tank. This lump adjusts its volume automatically as liquid nitrogen is either loaded or expelled. The GN_2 pressurization ullage is represented by another Fluint lump, which also automatically adjusts its volume according to tank conditions. These two lumps are linked by a Fluint Iface, which simulates the interface of the GN_2 to the LN_2. The sum of the GN_2 and LN_2 lump volumes is automatically conserved.

Both LN_2 and GN_2 lumps are contained within a representation of the LN_2 run tank. This tank model is a model on the Sinda side, and is represented by a series of approximately 10 tank sections, vertically stacked. Each tank section contains a "main" thermal node that contains the section's thermal mass, and massless thermal nodes on the inner and outer section surfaces. Adjacent tank sections are connected with appropriate longitudinal thermal conductors. All tank material properties are temperature-dependent.

The model contains logic that tracks the liquid nitrogen quantity remaining. The LN_2 level in the tank is computed from this quantity. From the LN_2 level, the model enforces thermal ties between the LN_2 and the tank wall inner sections that are covered by that LN_2. Any tank inner wall sections that are not covered by LN_2 are assumed to be immersed in the GN_2 pressurant and appropriate thermal ties between those wall sections and the GN_2 ullage are established. Heat transfer directly between the LN_2 and GN_2 is neglected at this point, and the mechanism responsible for ullage collapse is cooling of the GN_2 ullage by free/forced convection with the exposed tank walls. The walls are initially cooled to thermal equilibrium with the LN_2. Figure 22 shows the results of the thermal model with the ullage temperature plotted as a function of time. Because of the transient nature of this type of model, only a transient model was performed.

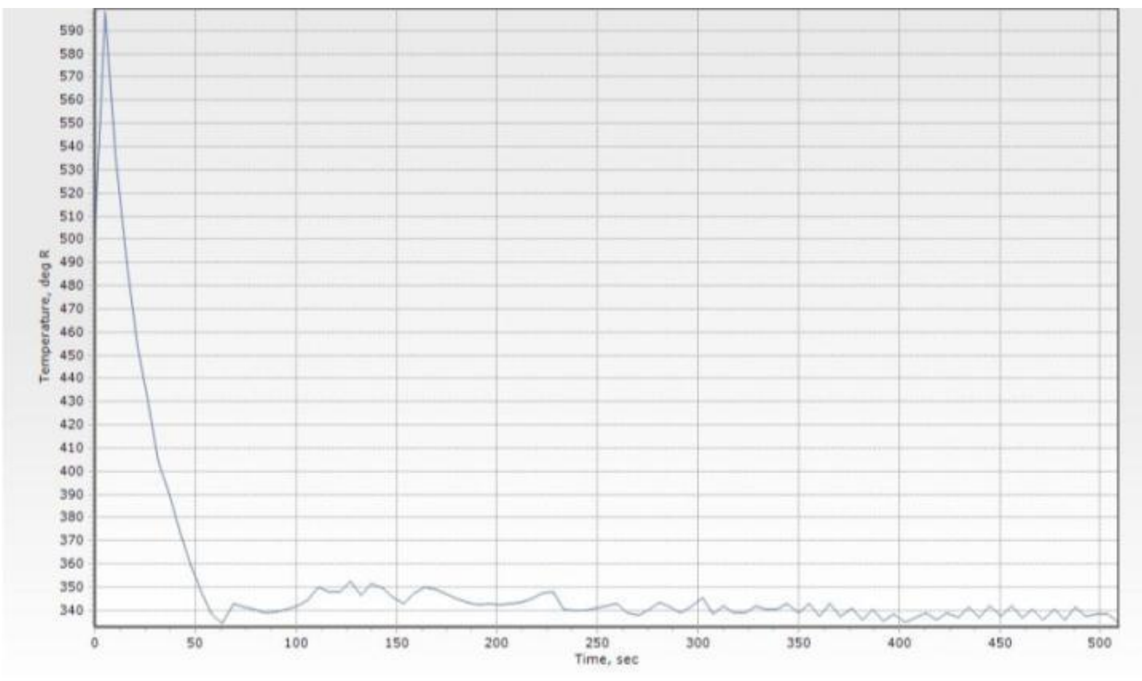

Figure 22. Sinda/Fluint LN_2 Run Tank Ullage Temperature Predictions.

Future work will be focused on updating the steady state Sinda/Fluint model with the calibration data that was taken for the two gas venturis and cavitating venturi. Refining the model using initial shakedown runs will be the subsequent step.

VII. Summary

The Themis cold flow mixing study is scheduled to begin at the end of 2012. The experiment will simulate large density ratio fluidic mixing at supercritical pressures. This study will provide data for validating commercial CFD codes. Fluid simulant selection and facility design have been completed. The modular test article and instrumentation sections have been fabricated and are ready for installation into the facility. Sinda/Fluint models of facility operation have been accomplished to ensure confidence that sufficient pressure budget exists to run the experiment in the high pressure conditions of interest.

Current efforts are largely being focused on the revamping the outdated control room software, calibrating the facility pressure transducers, fabricating the hot-wire anemometer rake, and installing the test article. One of the final fabrication efforts will concern the test article back-pressure orifice sizing. Initial sizing analysis and installation hardware for the orifice have been completed. The final sizing will be accomplished concurrent with facility shakedown tasks.

It is expected that this test capability will provide an ongoing means to acquire experimental data in high pressure regimes. This should allow for a greater understanding of the physical mechanisms that govern the complex interactions associated with fluid mixing, especially at supercritical pressures. Such data will fill a void in the scientific database with respect to the effects of supercritical conditions and high density ratios. This data can serve as an anchor for M&S programs which are used to design hardware that must operate in these regimes.

VIII. Acknowledgments

The extensive analysis and facility work associated with making this effort possible has required the support of many experienced individuals. Key top level support from Liquid Rocket Engine Branch Chief Dr. Richard Cohn and Technical Advisor Dr. Greg Ruderman has given this program the motivation, technical support and funding so critical to the effort's existence. Invaluable scientific analysis for this project has come from Principal Investigator Dr. David Forliti and Dr. Farhad Davoudzadeh. Support work from multiple disciplines includes the efforts of the following people: John Stephens, Jamie Malak, Alan Pate, Jennifer Nathman and external organizations including Flometrics Inc., Exquadrum Inc., Florida Commercial Propulsion and Power, and Advatec. Special thanks to the critical reviews, feedback and advice of AFRL personnel.

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